

OPTO-ELECTRONIC GENERATION OF LOW-JITTER PULSED SIGNALS

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There has been a great deal of interest in low time-jitter high-repetition-rate pulse generation. The interest stems mainly from fiber-based high-data-rate communications and optical ultra-fast analog-to-digital conversion applications [1]. In these applications, the timing jitter of pulsed signals can be a limiting factor for obtainable communication speed or sampling rate. Recently, actively mode-locked erbium-doped lasers (EDFL) have been demonstrated to be able to generate stable short pulses at 10 GHz and higher [2-4]. This kind of devices is particularly attractive not only because of the all-fiber approach, but also because of its compactness and environmental stability. In an actively mode-locked laser, the pulse-to-pulse jitter is ultimately limited by the phase noise of the mode-locking microwave source (typically electronic frequency synthesizers). On the other hand, opto-electronic oscillators (OEO) using fiber delay lines have been shown capable of generating microwave frequency with extremely low phase noise [5]. Therefore, one can take advantage of the low phase noise of an OEO for ultra-low jitter pulse generation. In this paper, we will describe the development of a new low-jitter pulse generator by combining the two technologies. In this approach, the optical oscillator (mode-locked EDFL) and the microwave oscillator (OEO) are coupled through a common Mach-Zehnder (MZ) modulator as an integrated pulse generator, thus named coupled opto-electronic oscillator (COEO) [6].

The opto-electronic oscillator is a unique type of microwave oscillator that converts light wave energy into stable and spectrally pure microwave references. It achieves an effective high oscillator Q through the use of a long piece of single-mode fiber, as shown in Figure 1(b). The microwave signal is modulated onto the optical carrier, recovered by the photo-receiver after propagating through the long fiber delay line, and then fed back into the modulator with proper phase and gain to complete the oscillator loop. The combination of the low transmission-loss and the long delay time through the optical fiber allows the effective high Q for the resonator. It can be shown that the spectral density of the phase noise at a given offset frequency is inversely proportional to τ^2 , where τ is the delay time [5]. By using a 6-km long fiber, for example, a phase noise of below -140 dBc at 10 kHz offset frequency can be obtained at 10 GHz, which is 40 dB lower than any commercial synthesizer. Further phase noise reduction is possible through carrier suppression technique [7].

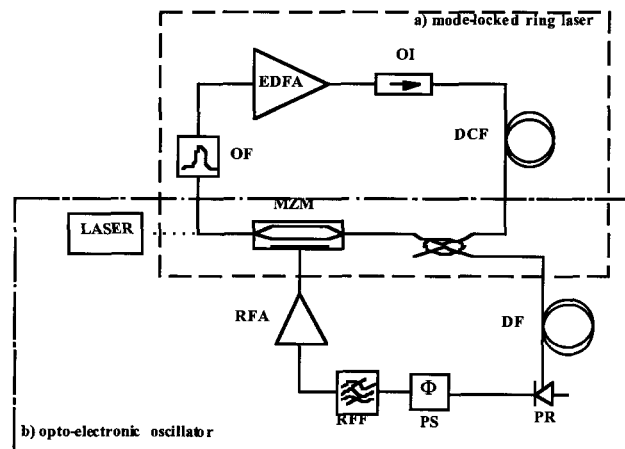


Figure 1. Schematics of a COEO with the mode-locked EDFL in a ring configuration. Dashed frames show separately a) the mode-locked laser and b) the OEO. OI: optical isolator; OF: optical bandpass filter; DCF: dispersion compensating fiber; MZM: Mach-Zehnder modulator; RFA: rf amplifier; DF: delay fiber; PS: phase shifter; RFF: RF bandpass filter; PR: photo-receiver.

The simplest mode-locked EDFL consists of a fiber ring loop with an erbium-doped fiber amplifier (EDFA) as the gain medium and a MZ modulator as the mode-locker, as shown in figure 1(a). When a microwave signal is applied to the mode-locker with a frequency equal to an integer number of the free spectral range of the laser cavity (known as harmonic mode-locking), it strongly modulates the intra-cavity optical signal and therefore couples all the relevant intra-cavity modes. Recently, there have been several approaches shown to have successfully generated stable short pulses. To reduce the polarization sensitivity, all polarization-maintaining (PM) fibers can be used as in reference [3]. The polarization sensitivity can also be circumvented by using the sigma laser configuration without using all PM fiber as demonstrated in reference [2]. Yet reference [4] demonstrated stable pulse generations even with non-PM loop. To achieve ultra-short pulses below Kuizenga-Siegman's limit [8], non-linear pulse compression effect such as soliton-assisted or additive-pulse mode locking has to be used. The pulse-shortening effects, together with spectral narrowing effects, are apparently necessary for stable pulse generation. In most of these cases, however, it is shown that the lowest jitter obtainable is limited by the phase noise of the driving microwave synthesizer. [4,9]

In the combined COEO approach, the external laser source in an OEO is replaced with the EDFA-based mode-locked laser as illustrated in Figure 1. The modulator in the OEO is also the mode-locker in the EDFL. The OEO derives the microwave signal from the beat-note of the mode-locked laser, properly filtered and amplified and phase-shifted, and fed back to drive the mode-locker. In the absence of the fiber delay, it resembles a regeneratively mode-locked laser. However, the addition of the delay fiber is non-trivial. It makes the loop into an oscillator capable of producing low phase-noise signals. The narrow bandwidth of the oscillator requires the mode-locking frequency to be in synch with the oscillator. The synchronization can be maintained by using a phase-locked loop. There are interesting regions of the COEO operation. At very low microwave drive level, for instance, the EDFL behaves like an injection-locked "amplifier" for the microwave because of the strong mode-locking tendency near resonance. It can provide enough gain that the OEO oscillates without an electronic amplifier in its loop. In the steady pulse output region, it is clear that the two oscillators in the COEO are strongly coupled. There exists the effect of amplitude-to-phase-noise conversion. Therefore, the amplitude stability of the pulse train affects the phase noise of the OEO and vice versa. It remains to be seen whether the combined system of a COEO can achieve a low pulse-jitter performance level comparable to that one expects to achieve with a direct OEO driven mode-locked laser. Based on the results of previous OEO studies, we expect to achieve a 10 GHz pulse train with pulse jitter of less than 5 fs. Such stable pulse source from an integrated opto-electronic system will find many applications in high-speed optical communications and fast optical data sampling. We are also studying the phase and frequency relationship between the rf generated from the OEO loop, and that obtained from the short optical pulses, and will report on it.

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